The increasing trend of the urban heat island intensity

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ABSTRACT

This paper examines the urban heat island intensity in detail in the city of Manchester, UK. An increasing intensity is found over time. The urban heat island intensity (UHII) data is examined in more detail giving relationships between weather parameters, cloud cover, wind speed and the urban morphology. The urban heat island intensity in Manchester has a highly significant rising trend which by the end of the century could add 2.4 K to the average annual urban temperature, on top of the predicted climate change increase. An analysis of the urban morphology showed that the urban site had indeed become more urban over 9 years of the study, losing green spaces which mitigate against the UHII.

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1. Introduction

The urban heat island intensity (UHII), the difference in temperature between an urban site and a rural site, is a measure of the urban heat island (UHI) effect. The UHI means that cities and towns are warmer at night than rural areas due to the absorption of the sun's radiation in the urban concrete and buildings, the fact that the urban buildings are shaded at night from heat loss to the cold clear sky and that there are heat gains in the urban areas due to cars and transport and buildings' energy use. This is important in the design and energy assessments of buildings in urban areas. It will be especially important in the future with climate change and potential global warming as the temperature is likely to increase and the UHI will add to it. Recent measurements in Manchester show a summer maximum urban heat island intensity of 8 °C. Climate change,

UKCP09 projections (UKCIP, 2016), indicate that summer mean temperatures in the north west of the UK could rise by 5 °C (50% probability, 7 °C top of the range) by the 2080s (high emissions scenario). The UHI will add to the urban area temperature on top of climate change.

The UHI is important as buildings need to cool off at night to get rid of their stored heat. Research in Manchester (Lee and Levermore 2013), modelling an interwar house indicated 3 K rise in internal temperature for a modest UHII of 5 K with a 60% rise in discomfort hours in 2050. Overheating in summer is also a problem for modern, low energy, well insulated houses (Good homes alliance, 2013) climate change and overheating: opportunities and risks for designers and the supply chain. London: The Building Centre, 2013. http://www.goodhomes.org.uk/events/138 (accessed 14 November 2013). This overheating results in the occupants having difficulty sleeping and possibly resorting to installing fans or full air-conditioning leading to more electricity consumption. Non-domestic buildings are similarly affected and even low energy non-domestic buildings utilising natural ventilation, have greater difficulty discharging their stored heat overnight in urban centres due to the UHI maintaining a warmer microclimate around them.

The UHI is probably a contributor to the considerable performance gap of new buildings between the declared design energy consumption and the actual consumption, the latter being between 1.5 and 2.5 greater than the former (Kimpian, 2013).

All these problems will be even worse as the UHI increases as this paper suggests, especially for Manchester, UK.

2. Manchester UK results

Fig. 1 shows the location of Manchester UK.

For Manchester, UK, the weather data at Hulme, just 2 km south of the city centre was available for a number of years. As it is not in the true centre of the city the UHI effect measured here would be expected to be slightly diminished by comparison with the true centre. The rural site is actually Manchester Airport, referred to as Ringway, which is about 12 km from the city centre Hulme and Ringway are UK Met Office sites. But since
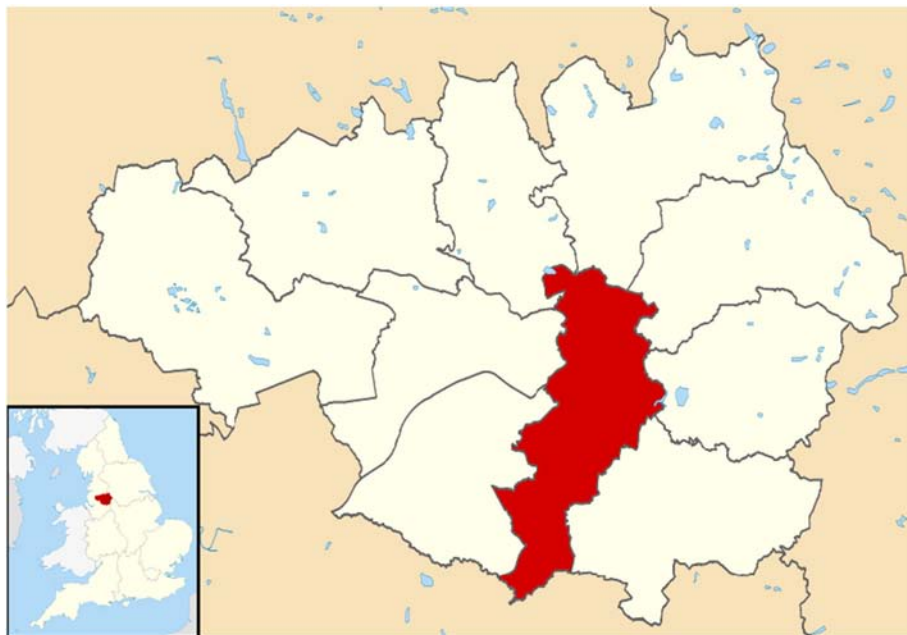

Fig. 1. The main map shows Manchester City (red) within Greater Manchester (light grey). Inset shows Manchester UK in the North West of England, UK.

2005 the Met office site Ringway was replaced by a site at Woodford. Woodford is a site about 11 km south east of Ringway. It is a more rural site next to a small airfield next to an aircraft factory. There are 132,992 hourly measurements of UHII as measured by the difference in temperature between Hulme and Ringway/Woodford during the years 1996 to 2011. The first measurement was at 1 am on 1st January 1996 and the last measurement at 11 pm on 31st December 2011, implying a potential set of 140,256 UHI hourly values, but there are a small proportion (5.2%) missing. These missing values should have no significant impact on the conclusions reached in this paper.

Fig. 2 shows the yearly averages for UHI. There is a clear upward trend in time.

The fitted trend line:

$$UHI = 0.021 * YEAR - 40.6 \tag{1}$$

has a statistically significant (P < 0.1%) slope of 0.021 °C per annum. If this trend were to continue then over the century the UHI would be 2.42 °C. This is approximately equal to the lower predictions of climate change and is in addition to climate change.

This set of yearly means (each point representing 8760 hourly values) has a minimum of 0.479 °C (in 1997), a maximum of 1.004 °C (in 2010) with an overall average value of 0.762 °C. It is also important to re-alise that the individual hourly measurements show much variation about this trend line (residual variance of 0.776 °C) and hence it is not always a positive number. In the data its values range from − 11.00 °C to 12.90 °C. These extreme values may have arisen as a result of recording errors at one or other site at that time on that particular day. The assumption in this work is that any such errors are randomly distributed and relatively rare, so inducing no systematic bias in the data or weather fronts crossing the urban and rural sites at different times.

3. Manchester urban morphology

Fig. 3 shows the location of the urban measuring station in Hulme, part of Manchester City. It is quite built up but mainly with low rise buildings.

Fig. 4 shows the digitised areas of green space near to the measurement station. It was possible to assess the green space and its changes between 2000 and 2009. It can be seen that the green area has reduced by up to 11% over the whole area shown although it is only a 1.5% reduction within 200 m of the station (the smallest circle) (Levermore et al., 2015.

4. Manchester climatology

Although the change in UHII is considered to be mainly due to the reduction in green areas around the urban site of Hulme the weather could also have been changing as well. The UHI is influenced by the cloud cover and wind speed. The UHI reduces as both increase and vice versa. Fig. 5 shows that the wind speed has indeed reduced a little but the correlation with time is poor indicating that it is almost insignificant.
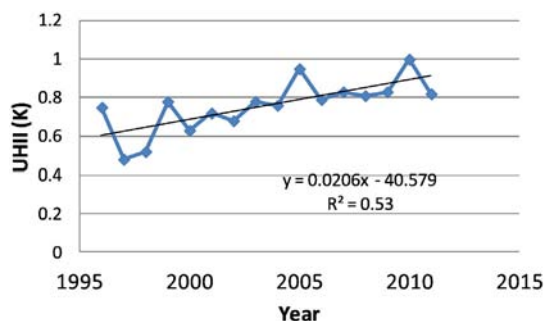

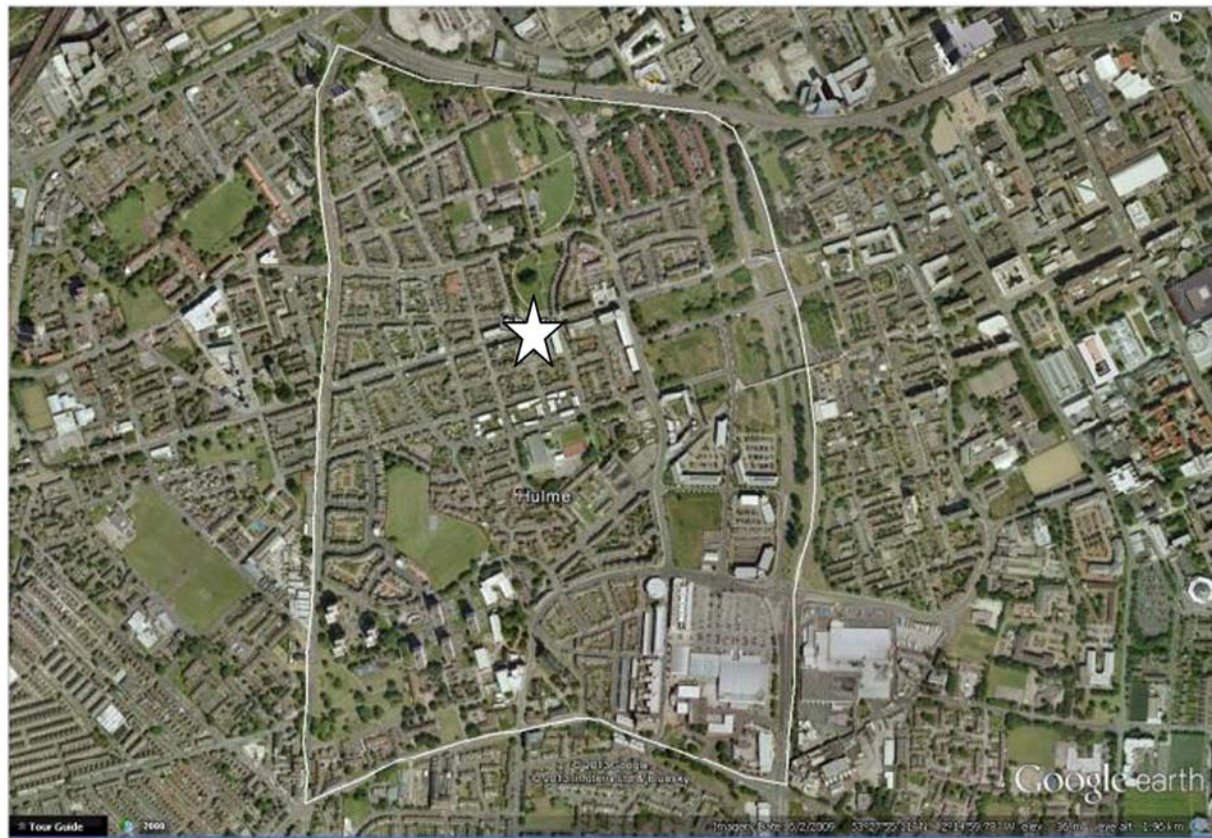**Fig. 2.** UHI Yearly averages plus trend line for Manchester UK.

Fig. 3. The area around Hulme, the urban site (weather station site shown by star) (Google map).
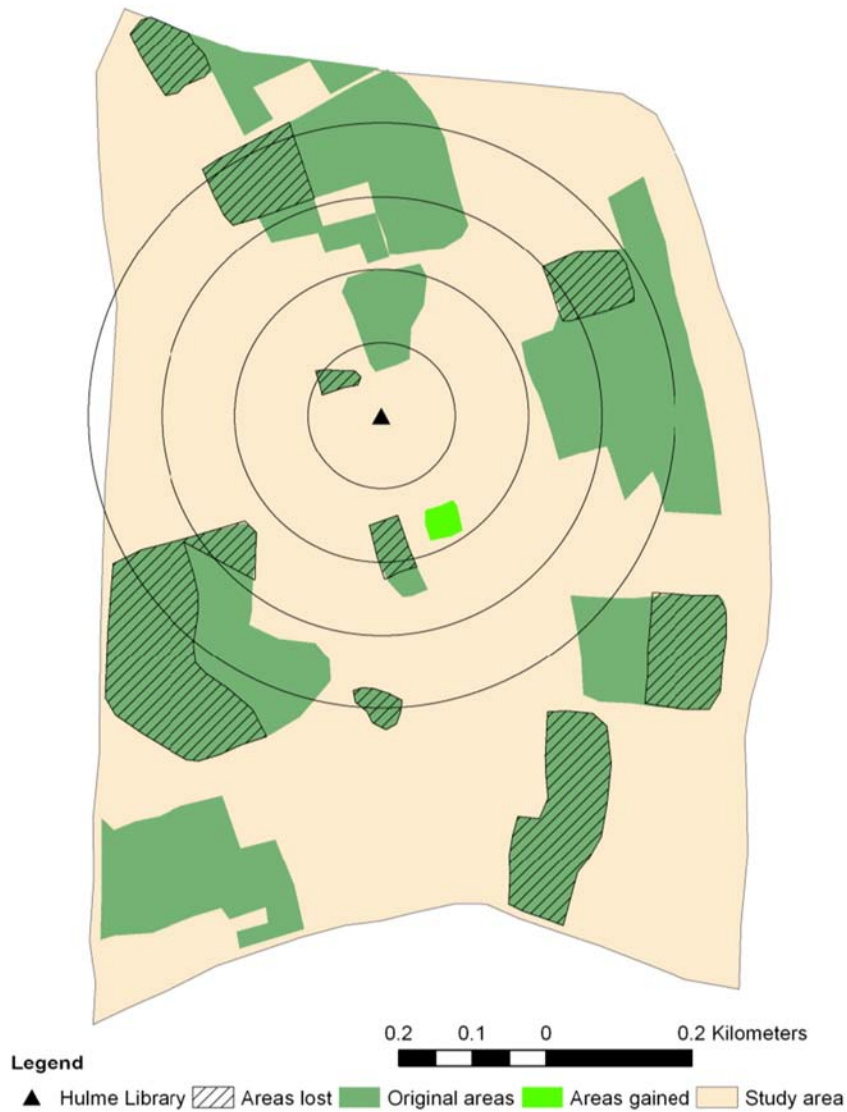
Fig. 4. Digitised areas of green space relative to the zones of assessment.

Fig. 6 shows a more significant but slightly lower reducing trend with time.

5. Manchester multi-parameter modelled urban heat island intensity

Although the morphology of the areas around the primary measurement site (Hulme) is changing with time, losing green areas, the local climate has changed slightly as shown above. To examine the influence of the local climate on the UHII a statistical model was made from the hourly data for the urban and rural sites (Levermore et al. 2015). This was achieved by using the multiple regression facilities of the statistical
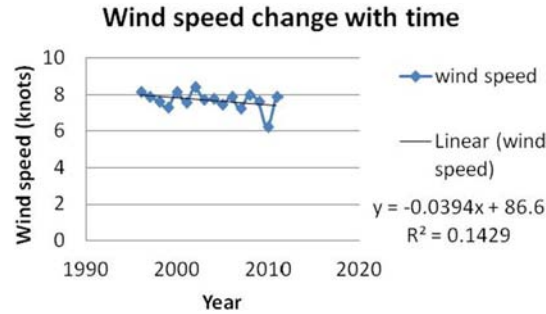
Wind speed change with time

Fig. 5. The change of wind speed at the rural site over time.

package SPSS. After fitting, the matched pairs of the sine and cosine linear model terms used for the diurnal and seasonal variation were each combined into single nonlinear sine terms incorporating a phase shift. The following formula was obtained:

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_5x_5 + b_6x_6 + e \tag{2}$$

where the dependent variable

$$\begin{aligned} y &= \text{UHI} \ (K) \\ &= (\text{Hulme temp} - \text{Ringway temp}) \end{aligned} \tag{3}$$

and the six predictor variables are:

$x_1 = $ Year-2000

$x_2 = $ air temp in °C at Ringway truncated above zero

$x_3 = $ wind speed at Ringway truncated at 10 knots

$x_4 = $ wind speed (knots) plus cloud cover (oktas) truncated at 14

$x_5 = $ SIN $(2\pi((\text{MONTH} = 1.2, ...,12) + 1.248)/12)$

$x_6 = $ SIN $(2\pi((\text{HOUR} = 0.1, ...,23) + 5.646)/24)$

The residual error term was modelled as having a normal probability distribution:

$e \sim N(0, 0.553)$

The individual regression coefficients were found to be:

$b_0 = 1.834954$ $b_1 = 0.018173$ $b_2 = -0.235607$ $b_3 = -0.016058$

$b_4 = -0.091833$ $b_5 = 0.104268549$ $b_6 = 0.21678237$

Although this model is for hourly values it was used for yearly average values.
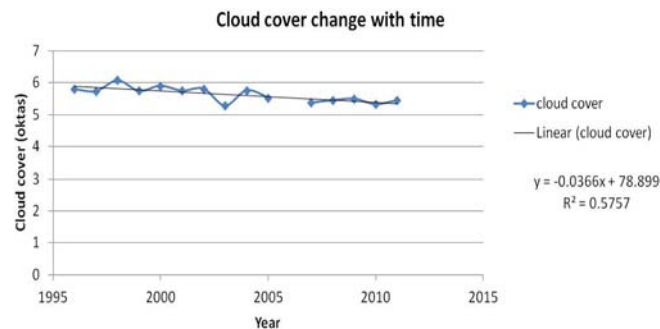
Cloud cover change with time

Fig. 6. The change of cloud cover with time at the rural site.
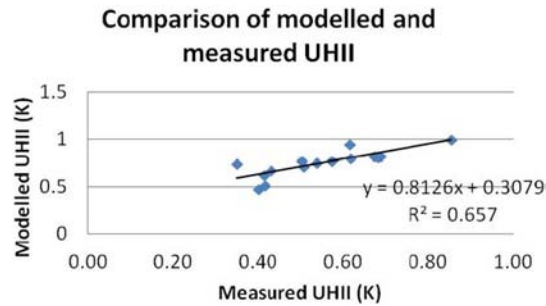
Comparison of modelled and measured UHII

Fig. 7. The accuracy of the SPSS-based model of the UHII for the annual data for all 15 years.

The sine terms averaged over a year disappear as do the monthly sine terms. Also the air temperatures truncated above zero disappears as the average air temperature is above zero.

However, the model using yearly averaged parameters produced a reasonable correlation with the averaged values from the measured data (see Fig. 7). Although there is some bias in the model, evidenced by the linear trend line not going through zero, the model is useful for comparing the influence of the cloud cover and wind speed on the UHII.

Fig. 8 shows the individual contributions from the model to the UHII. The wind (x_3 with b_3 coefficient) has little influence to the increasing UHII with time. The increase is very shallow with a slope of 0.0006 K year^{-1} and a poor correlation (R^2 of 0.1429). The cloud is more influential (x_4 with b_4 coefficient) but the Year of the average UHII is highly influential. This indicates that non-weather factors such as the urbanity most likely contribute to the increasing UHII.

6. Manchester rural site microclimatology

For determining the UHII the meteorological site outside the urban area was Ringway, Manchester Airport. This is not a fully rural site however, and the airport has expanded from 1996 to 2011 with a second runway and its infrastructure built. The official non-rural site was changed to Woodford, near Ringway but a more rural site. The site is a runway near an aircraft manufacturing site with a significant agricultural area of fields
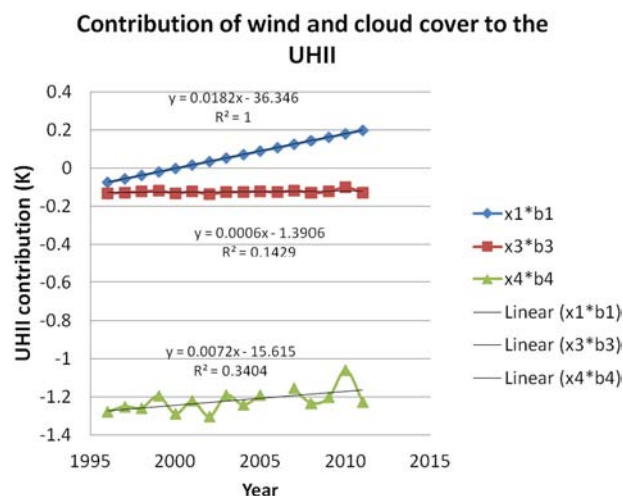
Contribution of wind and cloud cover to the UHII

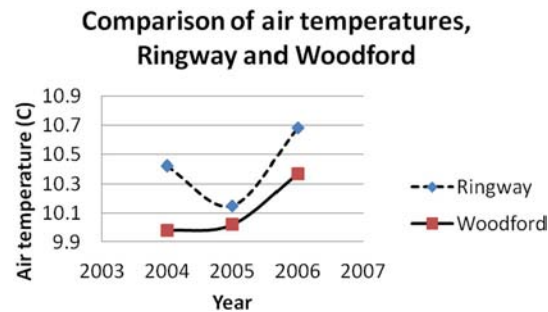**Fig. 8.** The contribution of wind and cloud cover to the increase of UHII over time.

Comparison of air temperatures, Ringway and Woodford

Fig. 9. The comparison of the air temperature at the "rural" sites, Ringway and Woodford.

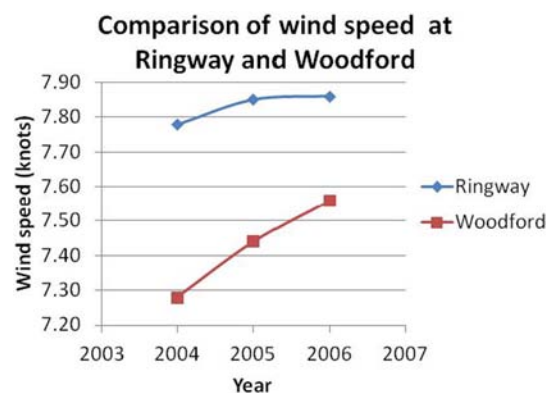## Comparison of wind speed at Ringway and Woodford

Fig. 10. The comparison of the wind speed at the "rural" sites, Ringway and Woodford.

surrounding it. There were three years of overlapping weather data for both Ringway and Woodford. Fig. 9 shows the higher air temperatures at Ringway, a small UHI existing there. This would lessen the actual UHII measured in the urban area of Hulme. However, the wind speed at Woodford is significantly lower than Ringway (see Fig. 10). As the wind disperses the UHI this counters the air temperature increase at Ringway.

7. Conclusions

In Manchester, UK, the UHII is increasing with time. If it continues to rise it will be similar at the end of the century to the predicted rise due to global warming (UKCIP, 2016, Met Office, 2016, Lee and Levermore 2013). The cloud cover has reduced with time, contributing to the UHII rise a little. But this does not account for the significant rise. It is considered that the increased urbanity may well be the prime cause. The green area around the urban site has reduced by 11% over part of the period of this study (2000 to 2009). The UHII rise may actually be higher as the semi-rural site was Ringway (Manchester Airport) which has been expanded and has a slight UHII itself.

This increase in UHII has serious implications for buildings and occupants in Manchester. The buildings will become more overheated in the summer with the consequent discomfort for occupants. There is also the implication for the installation of more air conditioning and the increase in energy use and carbon emissions.

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